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ORIGINAL PAPER

Energy Recovery from Sugarcane-Trash in the Light of 2nd Generation Biofuels. Part 1: Current Situation and Environmental Aspects

W. Alonso Pippo · C. A. Luengo · L. Alonsoamador Morales Alberteris · P. Garzone · G. Cornacchia

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Abstract The importance of Sugarcane-Trash energy use, also called Sugarcane Agricultural Residues (SCAR) or Barbojo was analyzed in the light of 2nd generation Biofuels. The current challenges and opportunities of SCAR energy use were treated. An analysis focused on current Brazilian situation and experiences around the world, was carried out. The most probable routes for 2nd generation Bioethanol production suitability: Biomass to Liquid and Bio-enzymatic were compared in Brazil. The Brazilian Sugarcane Agro-Industry particularities and its influence on SCAR energy use were analyzed. The most probable use of SCAR, in a short and mid term, is as boiler feedstock. The key environmental aspects related to SCAR use were analyzed. The SCAR decomposition process and its influence into the CO_2 emission reduction were explained. The weed control effect of SCAR left in the field was examined.

Keywords Sugarcane-trash · Bioethanol · Waste · Energy · Environment

Abbreviations

BPST	Back Pressure Steam Turbine
BTL	Biomass to liquid
CEST	Condensing extraction steam turbine
CDM	Clean development mechanism
CNPq	Brazilian National Council for Scientific and Technological Development
CONAB	National company of supply
CONAMA	Brazilian National Council on Environment
CS	Center-south region
CTC	Sugarcane Cooperative Technological Center
db	Dry basis
ECN	Energy Research Center of the Netherland
EMBRAPA	Brazilian enterprise for agricultural research
FAPESP	Foundation for research support of the state of São Paulo
GHG	Green house gases
HHV	High heating value
IPCC	Intergovernmental Panel on Climate Change
LHV	Low heating value
MW_{th}	Thermal mega-watt
NNE	North-northeast region
PETROBRAS	Brazilian semi-public multinational energy company (*Petróleo Brasileiro S.A.*)
PNUD	United Nations Program for Development
PROINFA	National Program to promote the development of alternatives energy supplies
SCAR	Sugarcane agricultural residues (also called sugarcane-trash or barbojo)
SFS	Simultaneous fermentation and saccharification
SP	Sao Paulo State, Brazil

W. Alonso Pippo (✉) · C. A. Luengo
Grupo Combustiveis Alternativos DFA/IFGW/UNICAMP,
Barao Geraldo, C.P. 6165, Campinas, São Paulo, Brazil
e-mail: pippo177@yahoo.com

L. Alonsoamador Morales Alberteris
Energy Consultant, 3008 Boaires Ln., Louisville,
KY 40220, USA

P. Garzone · G. Cornacchia
ENEA Trisaia Research Centre. Prot-STP, SS106 Jonica,
Rotondella, MT, Italy

toe	Ton of oil equivalent
wb	Wet basis
WHO	World Health Organization

Background

The sugarcane is a prodigious gramineous that belongs to the so called C_4 plants (because the first product is 4-carbon sugar). These plants have the biggest potential of sunlight conversion capacity into biomass (until 6.7%) [1]. In fact, the average figures reported on sunlight conversion are about 1.5–3% [2, 3].

The main solid residues from sugar and ethanol production are sugarcane bagasse and sugarcane-trash (SCAR). Sugarcane bagasse is the fibrous waste that remains after the recovery of sugar juice via crushing and extraction. The SCAR is composed of sugarcane leaves (green and dry) and cane tops (Fig. 1). The introduction of mechanized sugarcane harvesting along with power cogeneration technology improvements in sugar factories and ethanol distilleries has radically changed the significance of the use of sugarcane agro-industry residues starting from the last two decades of the twentieth century.

Most commercial sugarcane varieties have bagasse average yield, 140 kg/ton of milled cane dry basis (db). A ton of bagasse (on a 50% mill-wet basis) (wb) is equal to 1.6 barrels of fuel oil on an energy basis [MJ/kg] [4]. It is well known that SCAR energy content (db) is similar to bagasse energy content.

It is a common practice to use bagasse energy for cogeneration during milling season in the sugarcane agro-industry. However, a negligible amount of SCAR is currently used for cogeneration at sugar mill. Even though the SCAR energy content is similar to bagasse, unfortunately in many places it is burned-off just before harvest to facilitate an easier sugarcane stalks collection. Until today SCAR energy use in commercial scale is an unsolved question to the Sugarcane Agro- Industry.

The analysis to effectively introduce SCAR energy use at large scale is the goal of the present work. This analysis focuses on the better understanding of SCAR performance in the light of 2nd generation bioethanol arriving in the sugar industry. It was carried out regarding better SCAR energy use experiences around the world and focused on current Brazilian situation of this issue.

Importance of SCAR Energy Use

There are more than 90 sugarcane producer countries around the World, most of them are underdeveloped countries without fossil fuels reserves. The energy recovery from sugarcane residues disposal means a great chance for social development related to environmental issues and financial support through CDM Carbons Credits.

The world's sugarcane production has increased during the last decade (Fig. 2). For example, it processed more than 1,740 × 10^6 tons of sugarcane in 2008. This amount of sugarcane generated 435 × 10^6 tons of bagasse and

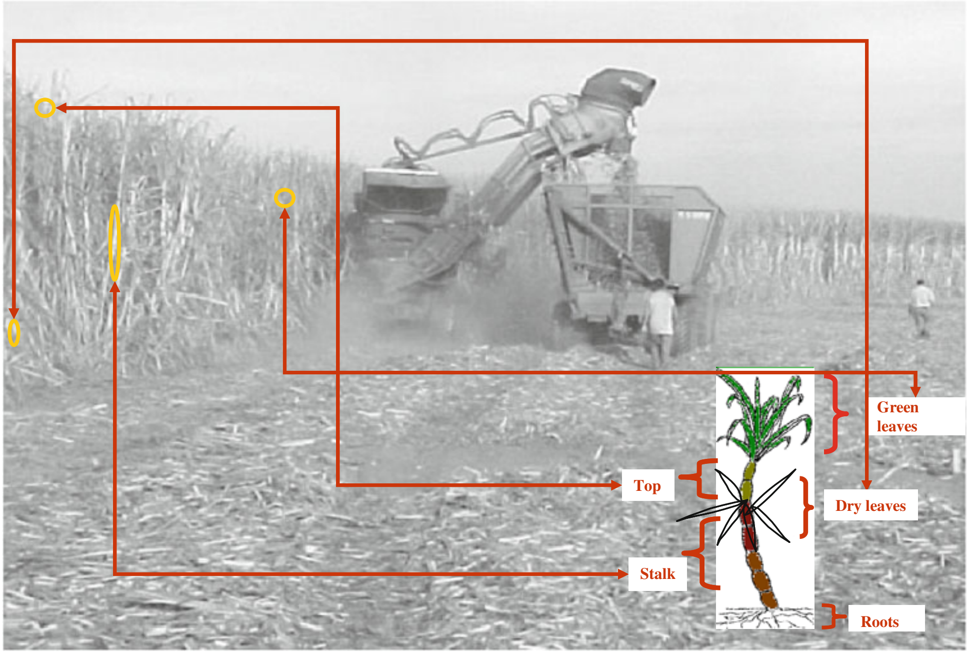

Fig. 1 SCAR component parts collected during sugarcane harvesting. *Source* Adapted by authors from [48]

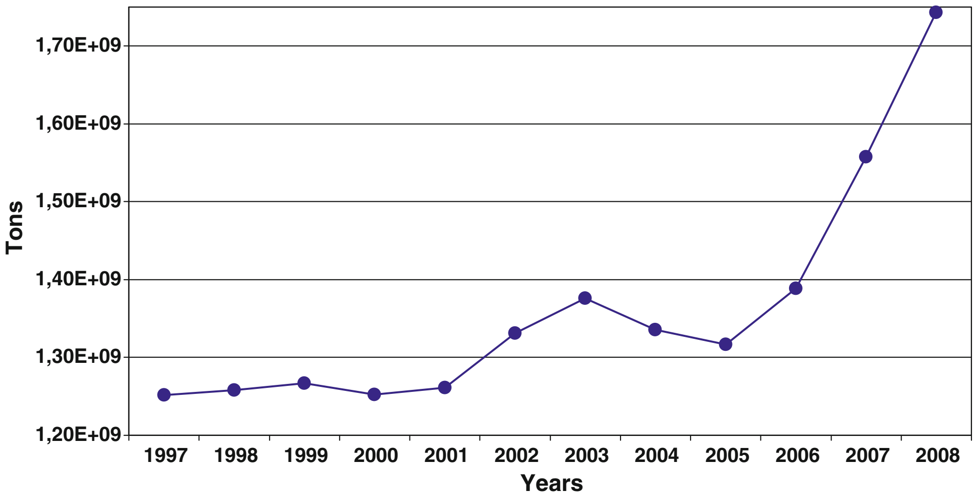

Fig. 2 World's sugarcane production 1997–2008. *Source* [49]

Table 1 Average sugarcane energy content of most used commercial sugarcane varieties

Sugarcane parts	1 ton of sugarcane	
	Mass (kg)	Energy (MJ)
Juice (sucrose + molasses + others) (dry basis)	142	2,257
Fiber residues (bagasse) (dry basis)	140	2,184
Sugarcane agriculture residues (SCAR) (dry basis)	140	2,184
Total	422	6,625

Source [6]

389 × 10^6 tons of SCAR. The energy content of this amount of SCAR could mean 12 × 10^6 toe.

On the other hand, several elements such as issues concerned with the GHG emissions, high oil price, the crops use for biofuels production versus food and other geopolitical factors associated with traditional oil supplies instability are encouraging the introduction of 2nd generation biofuels as a new opportunity obtained from biomass residues and lignocellulosic biomass.

SCAR represents 1/3 of total sugarcane energy content (Table 1). In others words, SCAR is the most important reserve of sugarcane energy unused until today. So, any step guided to increase sugarcane lignocellulosic biomass use at sugar industry must take into account the introduction of SCAR energy recovery in commercial large scale.

State-of-Art on SCAR Energy Use

In the last two decades numerous studies and researches have been carried out on sugarcane biomass residues energy use in the sugar factories. Most of publications on the subject are on bagasse [5–7], however studies and specific works on SCAR energy use are less known and have not received enough publication. Most of them are internal reports, personal communications or events participation [8–13].The conclusions taken from the current SCAR energy use state-of-art are the following:

1. The figure rate reported: SCAR weight/sugarcane stalk weight varies from one author to another, even though, the average rate figure is among 0.25–0.3 "as received", (wb) and 0.13–0.15 on (db).
2. The average rate between the tops weight and the leaves (green + dry) weight is 0.69–0.76/0.14–0.21.
3. The amount of SCAR that should be left on the field to get a weed control effect has not accurately been defined yet. Some authors suggest 15–20 tons of SCAR/hectare, others simply the 50% of the SCAR mass. Both figures mean a similar quantity for most of sugarcane commercial varieties.
4. The works [14] and [15] reported a HHV 17 MJ/kg (db) of SCAR.
5. It was reported in the work [16] that if all SCAR available in the sugarcane plantation is used, it would represent an increase of 1.62 times more biomass.
6. Taking a base of medium size sugar mill (7,000 ton of cane/day) with modernized cogeneration system (CEST-6,3 Mpa., 793 K; 380 kg of steam/ton of milled cane) and using SCAR as boiler fuel in the work [4] was reported an additional profit of $4.34USD/ton of cane. This means an increase from $18.66 USD/ton of cane to $23.00 USD/ton of cane when the SCAR is used as boiler feedstock.

In general, all mentioned works have evidence leading toward the SCAR energy use, but most of them recommend further studies about environmental feasibility considering the specific harvesting conditions. Although, it is accepted by all that sugarcane's burn off is detrimental to the environment, the burn of sugarcane before harvesting still being a widespread practice in Sugar Agro-industry. The burn of sugarcane does not allow any SCAR use.

Currently, SCAR is also partially used as animal feeding in some places. However, SCAR's low protein content and low digestibility for ruminant, swinish and others kind of animals impeding its use beyond 3–6% of cattle ration volume content.

SCAR Energy Use: Uncertainties and Particularities

Currently there are several reasons that explain the negligible amount of SCAR use as boiler feedstock at sugar factories. A summary of constrictions and particularities of SCAR use is shown in Fig. 3. Along with them, some concerns deserve to be mentioned:

1. For many years before the twentieth century, sugarcane industry main goal was the maximization of sugar and ethanol production taking advantage of cheap manual labor. The bagasse was burned inefficiently just to avoid environmental pollution without any perspective on higher energy efficiency of sugar-ethanol production process. It was not taken into consideration the bagasse energy and its potential capacity to cogenerate surplus electricity.
2. Sugarcane varieties grown until the twentieth century were developed mainly for sugar and ethanol production and not for energy production.
3. Current sugarcane harvesting methods and sugarcane harvesting machines have been developed to clean sugarcane-trash from sugarcane stalks and not for its recovery.
4. SCAR has been the less studied residue among all sugarcane residues. SCAR physics-chemical properties can be notably modified depending on used sugarcane harvesting method and also from one sugarcane variety to other, which is a main obstacle to generalize research's results.
5. SCAR sucrose content and chemical composition are not suitable for sugar and ethanol production. Therefore contrary to the bagasse delivered to factory in form of sugarcane stalks, without an additional transportation cost, there is an additional cost for SCAR's collection including its handling and deliver to sugar factory.
6. SCAR ash content is higher than bagasse and its higher contamination with soil particles also makes it less suitable for use in a common boiler (Table 2).

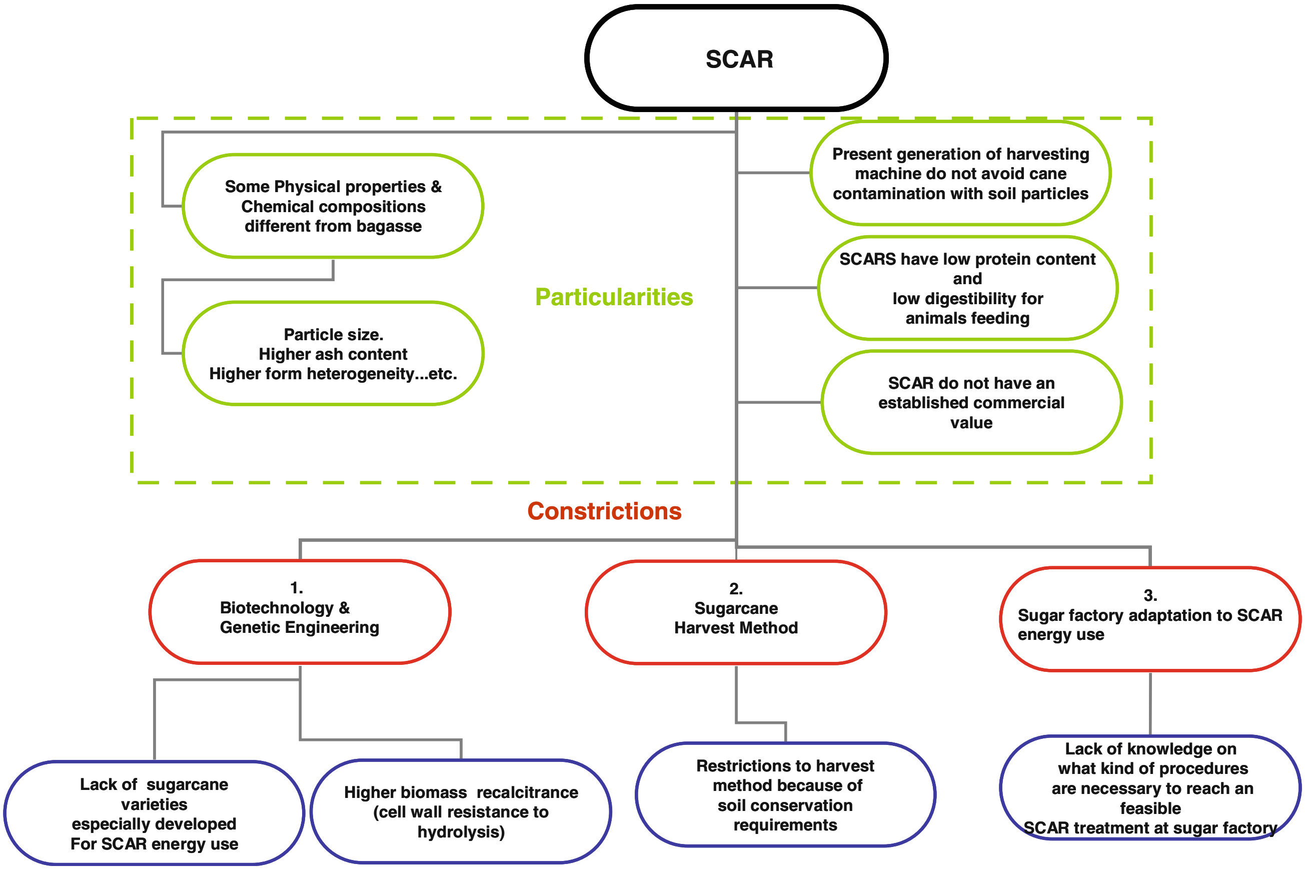
SCAR
Some Physical properties & Chemical compositions different from bagasse
Particle size. Higher ash content Higher form heterogeneity...etc.
Particularities
Present generation of harvesting machine do not avoid cane contamination with soil particles
SCARS have low protein content and low digestibility for animals feeding
SCAR do not have an established commercial value
Constrictions
1. Biotechnology & Genetic Engineering
2. Sugarcane Harvest Method
3. Sugar factory adaptation to SCAR energy use
Lack of sugarcane varieties especially developed For SCAR energy use
Higher biomass recalcitrance (cell wall resistance to hydrolysis)
Restrictions to harvest method because of soil conservation requirements
Lack of knowledge on what kind of procedures are necessary to reach an feasible SCAR treatment at sugar factory

Fig. 3 SCAR energy use uncertainties and constrictions

Table 2 SCAR and bagasse ash content

Reference	SCAR ash content (different authors) (%)			Average figure (%)
	[16]	[44]	[45]	
Ash	6–10	5.56	7.7	6.4–7.75
Bagasse average ash content				2–3

7 There is not sugarcane harvesting machines suitable to cut sugarcane on soils with slopes higher than 12%.

8 The sugarcane mechanized harvesting is unsuitable economically for small sugarcane producers or when the sugarcane yield is too low in general.

SCAR Energy Potential in the Light of 2nd Generation Biofuels Production

BTL Pathway

The main pathways for 2nd generation biofuels production at sugar industry are: biochemical (bio-enzymatic) and thermochemical (BTL) or a combination of both.

BTL pathway for biofuels production at modernized Brazilian sugar/ethanol plant was analyzed in [17] based on the results of the work [18]. The conclusions pointed out that at present level of technological development it is only possible foresee a potential advantage of BTL from GHG emissions viewpoint. However, there are at least three more reasons to indicate that BTL pathway is unsuitable for Brazilian sugar/ethanol industry in short and mid term. First, very high capital investment is necessary to introduce gasification technology in sugar industry; Second, most Brazilian sugar factories and distilleries are small or medium size and do not meet BTL scale requirements; Third, the Brazilian law forbids the use of diesel fuel in light vehicles and it seems to be that synthetic gasoline has not future in Brazil now ready to become the biggest Latin-American oil producer.

BTL pathway is promising for SynDiesel and synthetic gasoline production, but current Brazilian infrastructure used at distilleries is closer to bio-enzymatic pathway than to BTL technology. The capital investment needed for BTL technology implementation and the biomass plant size have been subject of research at ECN. The ECN study was based on Sasol–QP Gas to Liquid plant (GTL) in Qatar. The study concluded that—The heart of BTL plant is pressurized oxygen-blown slagging entrained flow gasifier: this technology was identified as optimum technology for bio-syngas production. The torrefaction is the optimum pre-treatment for entrained flow gasification. The capital investment needed for BTL plant is 60% higher than the GTL plant. This means an increase of $ 51800 USD/bbl day ($325.78 USD/l day) [19]. Concerning the optimal size of BTL plant the ECN work pointed out a range from 2,000 to 4,000 MW_{th} [19] .

Some Particularities on Brazilian Sugarcane Agro-Industry

In 2008 there were 343 sugar factories and ethanol distilleries in Brazil [20]. Although, the policy implemented by Brazilian government in the seventieth, (National Alcohol Program-*Pró-Álcool-*) was the key of sugarcane branch current success, the governmental ownership on Brazilian sugarcane agro-industry is null. However, since 2003 it is notable the participation and growing interest of government on sugarcane agro-industry through Ministry of Mines & Energy and enterprises like PETROBRAS[1] [21]. This last one recently stopped from being only an oil company to become an energy enterprise on all primary energy supplies.

PETROBRAS has begun to support research's projects on renewable energies carried out by public universities and research's centers. CNPq, FAPESP and research's support agencies from others Brazilian states are also playing an active role on the support of researches on sugarcane's energy.

A growing participation of foreign investment capital in Brazilian sugarcane agro-industry has taken place since last decade. Foreign partners are investing mainly on existing distilleries modernization and building new autonomous distillery[2] in the CS region. It has been estimated that foreign capital participation on sugarcane business doubled in Brazil from 2007 to 2010. Today foreign enterprises process 25% of all sugarcane in the country [22].

Because of sugar factories ownership's characteristic it is possible to find significant technological differences from one sugar factory to other one. Most of the state-of-the-art sugar factories and distilleries have been built starting from year 2000 in Paraná, Matto Grosso do Sul and SP states.

Although, there is huge bagasse energy potential, the export of surplus electricity from cogeneration is not a widespread practice in Brazilian sugarcane industry. For example, only 14% (48) of Brazilian sugar factories were connected to national electrical power grid in 2008. Only those connected factories have real possibility to export their surplus electricity. This figure represents only 21.9% of the total milled cane during 2007–2008 milling season in Brazil [20]. Also, this means that most of bagasse is still burned in low efficient conditions (2 MPa and 593 K boiler operational parameters; 500 kg of steam/ton of milled cane).

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[1] Brazilian Federal Government is the biggest shareholder. It owns 32% of Capital Stock.

[2] Autonomous distillery—The simultaneous production of sugar and ethanol is the rule of sugarcane industry. Most existent sugar factories have associated distilleries. The distilleries not associated with sugar factories are called autonomous distilleries.

The Federal Decree 5.025/2004 based in the law No. 10.438/April 26/2002 (PROINFA) was launched in 2004 to promote the sales of surplus electricity from renewable supplies. This Decree fixed a low price sale for electricity cogenerated from biomass and does not satisfy the profit expectation of majority of sugar factory owners. Because of the Decree results were not as expected by the owners, the surplus electricity is sold trough auctions. Even when the electrical power capacity sales trough auctions represent a better profit opportunity for sugar factory owners, still remain several unsolved questions concerning buyers-distribution enterprises. Some of these concerns are: the concessions conditions, the payment of connection to the public grid and costumer electricity prices, which are not regulated yet.

Concerning the sugar factory type 81 and 12% of total cane was milled in sugar mills with distillery annexes and autonomous distilleries, respectively, during 2007/2008 milling season [20].

The CS and NNE are the two main sugarcane producer regions in Brazil. CS is the biggest producer and it was responsible for almost 90% of all sugarcane processed during 2008–2009 milling season (Fig. 4). According to CONAB, 77% (264) Brazilian sugar mills and bioethanol distillery were working in CS, during 2007–2008 milling season [20]. The state of SP plays a principal role among CS states because 58% (153) of sugar mills and ethanol distilleries are located in SP. Regarding the yearly milling capacity of sugar factories existent in SP, 68% of sugarcane is milled in sugar mills and distillery with annual milling capacity $\leq 2 \times 10^6$ ton of sugarcane/year [23].

A distinctive characteristic of Brazilian sugar and ethanol agro-industry is that sugar factory owners, as rule; do not buy sugarcane from other plantations. The sugar factory owners own the sugarcane plantations, too. It determines that sugarcane delivered to sugar factories is harvested in the surrounding areas.

Until April 2008, 75% of sugarcane was harvested manually in Brazil [23]. In SP state 33% of green sugarcane is harvested mechanically. This situation is changing because SP state environmental law prohibits the burns of cane before its harvesting beyond year 2031 [24].

The sugarcane transportation by railroad practically does not exist in Brazil. The harvested cane is transported to sugar factories by articulated lorries. As rule the lorry payload capacity is 45 ton. The main road grid of SP state is the best road grid existing in Brazil. However, the conditions of municipal secondary roads (unasphalted roads) are not always good, that is why cane transportation becomes especially hard after raining. After delivering the cane to sugar factory the lorries come back empty to sugarcane's plantation in order to pick up a new load. So, the round trip should be use to calculate fuel consumption.

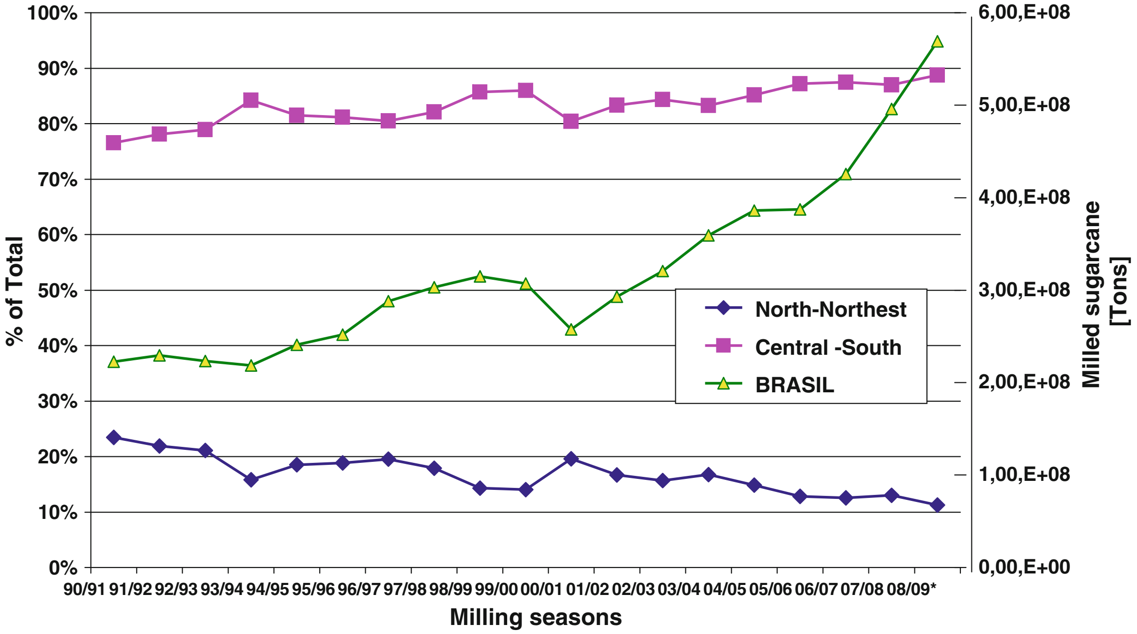

Fig. 4 Sugarcane milled by Brazilian factories. Milled cane % by regions NNE and CS. Milling seasons from 1990/1991 to 2008/2009. *Source* [20]

The current sugarcane average yield in SP is 83 ton of cane/hectare year and the average land used during a milling season is 80% of total sugarcane planted surface. An average figure of 15–20% of sugarcane area is used for roads and electricity power grid.

The sugarcane price for Brazilian condition varies from \$16.85 USD[3]/ton to \$22.47USD/ton.

BTL Perspectives in Brazil

Considering the optimal plant size mentioned in "BTL Pathway" section and the Brazilian sugar agro-industry particularities only one sugar factory in SP, (The Sao Martino sugar factory) has enough large installed power thermal capacity to reach the optimal size mentioned in the ECN study. Sao Martino is the biggest in SP [25]. During 2008–2009 milling season (210 days) a total of 8.004.221 tons of cane were milled in the Sao Martino factory.

Assuming a bagasse and SCAR content of 280 kg/ton of milled cane, an average LHV = 15 MJ/kg for both residues and the use of 50% of SCAR, Sao Martino factory should have an installed thermal capacity of 1,598 MW_{th} for a year round. When it is only considered the milling season period (210 days) the thermal capacity installed reaches 2,779 MW_{th} which is a recommended figure into ECN optimal range mentioned in the "BTL Pathway" section.

Most Brazilian sugarcane factories have a milling capacity smaller than 2 × 106 ton of sugarcane/year (four times smaller than optimal estimated milling capacity for BTL implementation. See "BTL Pathway" section). In other to implement BTL technology huge capital investment and infrastructure's changes should be made. Due to that BTL technology is almost impracticable in short-mid term in this country.

Bio-Enzymatic Pathway

The most used yeast breeds for bioethanol production are the *Saccharomyces cerevisiae* (SC). Currently, the best ethanol yield production using SC is about 0.46 g of ethanol/g of sucrose while the maximum theoretical yield figure is 0.51 of ethanol/g of sucrose [26–29]. An increase of 5% could be seemed as a negligible amount, but regarding the huge volume of ethanol production (millions liter/day) this "apparently" small increase plays an important role.

The main problems in order to increase bioethanol production yield are:

1 The simultaneous juice contamination by thousands undesirables fungus varieties which are "hungry" of sucrose competing with SC (The reaction mechanisms of these "undesirables" fungus has not been completely explained yet. So far this kind of contamination seems to be unavoidable.
2 The relative low capacity of known yeast to live in a substrate with high alcohols concentration.
3 The low SC thermoresistance.

Currently many new SC breeds are under research. The studies on SC genome have brought interesting news on microorganism's way of life. There are some encouraging results at lab scale, but it is too early to predict their successful introduction in bioethanol distillery at large scale.

The lignocellulosic bioethanol production should overcome several difficulties before its commercial production could be economical feasible. The main barriers to overcome are: biomass cell wall resistance to microbial and enzymatic attack (also known as biomass recalcitrance) [30] and lower cost cellulase production.

Several physic-chemical methods have been tested to separate lignin, hemicelluloses and celluloses. Among them: Steam-Explosion, acid hydrolysis, alkali hydrolysis and organ-solvent pre-treatment. The method selection depends on biomass type and specific conditions; there are not standard criteria to determine which one is better.

Others important questions concerning biomass hydrolysis and simultaneous fermentation-saccharification need deeper studies and currently are under research.

An important research's goal for the 2nd generation bioethanol is to lower the cellulose enzymes production cost. The bioethanol production cost from wood residues, SCAR, corn stover and others similar feedstock using cellulase is currently prohibitive.

Generally, low cost ethanol producing SC breeds use only the hexoses contained in the SCAR. The SCAR conversion yield into bioethanol under these conditions is lower than 20%. The challenge is to use the pentoses for its conversion into bioethanol too [31]. This way the SCAR conversion yield into bioethanol could increase up to 50–60%. In the Fig. 5 it is shown a scheme of SFS including pentoses's conversion.

There are several difficulties to reach the simultaneous hexoses-pentoses fermentation. In the case of SCAR the main of them is SCAR high ash content and particle size heterogeneity. SCAR and bagasse chemical compositions are shown in Table 3.

Comparing the bagasse and SCAR chemical compositions it is noticeable that from lignin separation viewpoint SCAR would be better (only 13% of lignin content) while bagasse lignin content almost doubled it. However, bagasse particle size homogeneity, low production cost, low ash

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[3] 1USD (March, 2010) = 1.76 Brazilian Real.

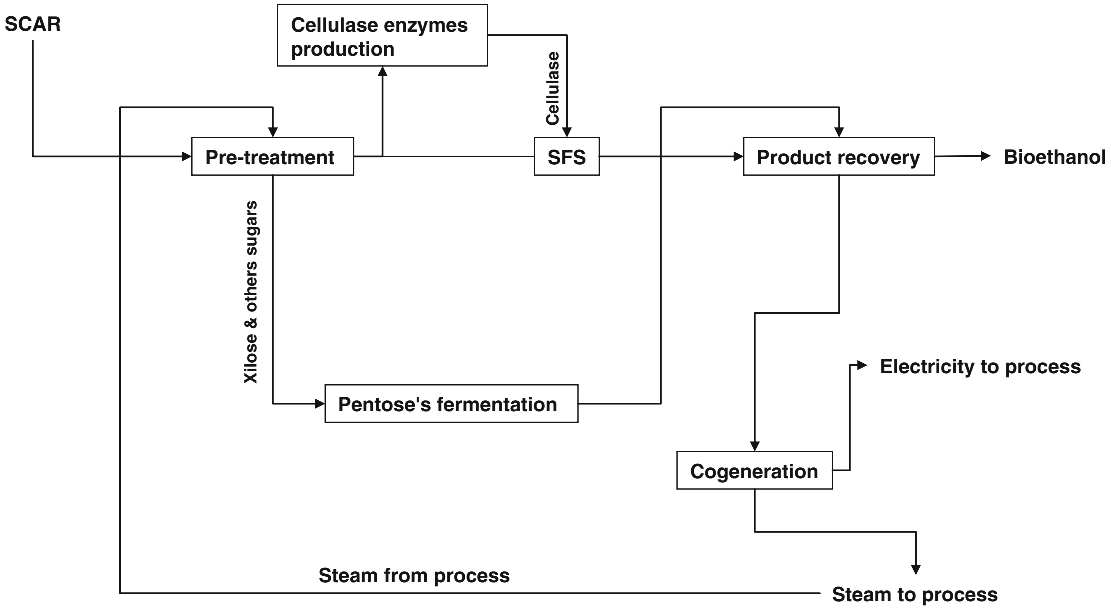

Fig. 5 Schematic diagram of SFS for bioethanol production starting from SCAR. Pentose’s fermentation included. *Source* Adapted from [50]

Table 3 Sugarcane bagasse and SCAR chemical composition

Component	Chemical composition [% of weight]	
	Bagasse	SCAR
Cellulose (hexoses)	46	48
Hemicellulose (pentoses)	27	27
Lignin	23	13
Pectin	0	4
Ash	4	8

and pectin contents makes it a better choice for 2nd generation bioethanol production. The use of bagasse for 2nd generation bioethanol production instead of its traditional use as fuel for the cogeneration in the sugar factory has raised some new concerns on its possible substitute.

The classical cogeneration scheme of a sugar factory (milling capacity: 7,000 ton cane/day) is shown in Fig. 6. In the new conception a part of bagasse will be used for 2nd generation bioethanol production and the SCAR will be used to substitute this bagasse amount during cogeneration (Fig. 7).

Although, the works on lignocellulosic materials have been carried out during 10–20 years it is not clear to the specialists, when the readiness level of lignocellulosic bioethanol technology will reach commercial stage. Most optimistic opinions say the commercial stage of bioethanol production from sugarcane bagasse is 10–12 years away. Even, if 2nd generation bioethanol production at large scale could be implemented right now, the most probable use of SCAR today and in the next future will be feedstock for cogeneration in the sugar factories.

SCAR Availability and Morphology

The sugarcane stalks contain the juice and the bagasse. The stalks are milled to extract the juice for sugar and ethanol production. Sugarcane bagasse is the fibrous waste that remains after recovery of sugar juice via crushing and extraction.

Among sugarcane operational indexes most important, from logistical and technical–economic viewpoints, are sugarcane yield ($\text{Cane}_{\text{yield},}$ ton of sugarcane/ha) and sugarcane SCAR content. Sugarcane total weight can be expressed as it is shown in (1).

$$\mathrm{TW}_{\mathrm{SCAR}} = \mathrm{W}_{\mathrm{STALK}} + \mathrm{W}_{\mathrm{SCAR}} \quad (1)$$

where, $\mathrm{TW}_{\mathrm{SCAR}}$—sugarcane total weight; $\mathrm{W}_{\mathrm{STALK}}$—sugarcane stalks weight; $\mathrm{W}_{\mathrm{SCAR}}$—SCAR weight.

The smaller is SCAR content among sugarcane stalks delivered to sugar mill, the better will be juice quality for sugar and ethanol production. Therefore until few years ago all technological efforts of sugar agro-industry were to avoid the SCAR delivery to sugar factory.

SCAR Availability

Since the last two decades of twentieth century until today many researches have been done on SCAR availability i.e. $\mathrm{W}_{\mathrm{SCAR}}/\mathrm{W}_{\mathrm{STALK}}$ ratio [7, 10, 11, 32].The most significant and largest experiences on SCAR availability were carried out in Cuba [8], Brazil [33]and in Mauritius Island [16]. Due to differences in methodology used during this studies it is not possible accurately compare between them.

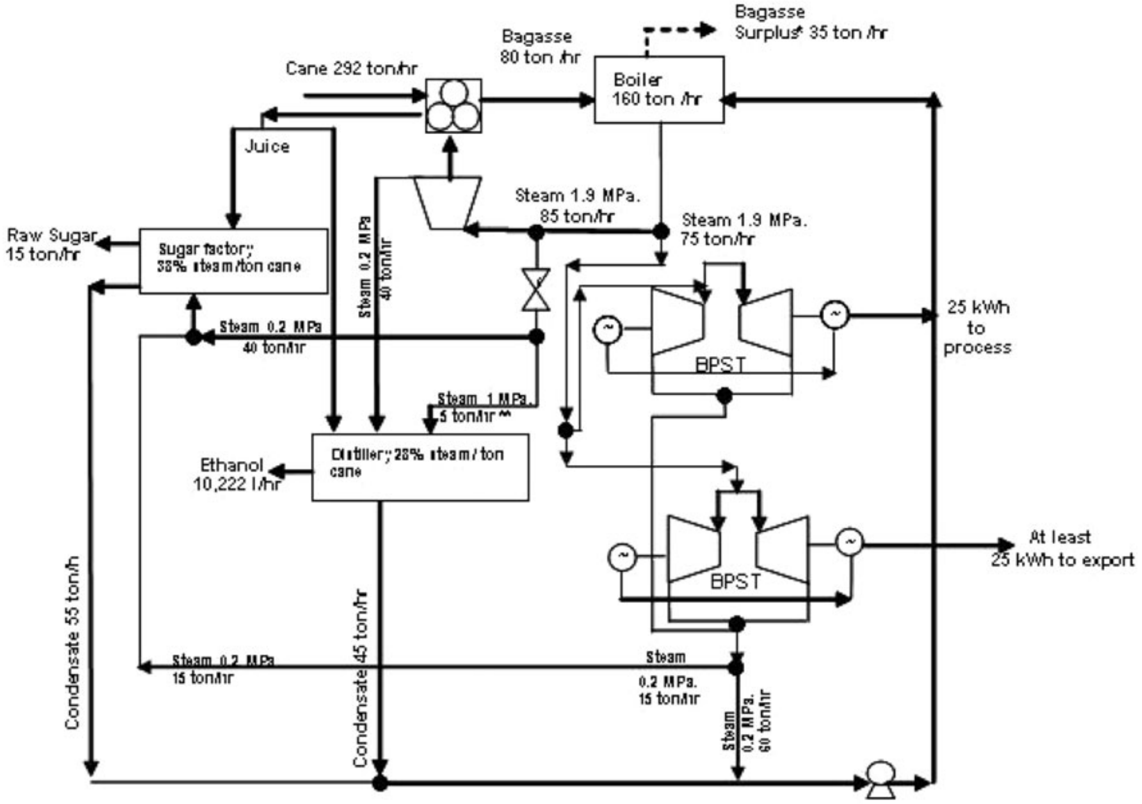

Fig. 6 Sugar mill cogeneration scheme (7,000 ton of cane/day); BPST and simultaneous sugar-bioethanol production. *Source* [51]

A study on W_{SCAR}/W_{STALK} ratio carried out by fifteen institutions around the world is shown in Fig. 8. The results show significant variances among them (from 2% Sao Paulo to 35% Hawaii) and an average figure of 11,33% (dry basis).

The results of combined work (PNUD-CTC) carried out in Piracicaba and Riberao Preto, SP; Brazil, during milling seasons 97–98 and 98–99, concluded that average W_{SCAR}/W_{STALK} ratio was 14% (140 kg of SCAR/ton of cane in the field dry basis) [33].This value matches the results obtained by [8], [34] and [32].

Several specialists reported different SCAR amount to be used without diminishing its weed control effect. The figure varies from one author to other. In general is accepted that 50% of total SCAR mass could be left on the field not affecting SCAR weed control effect.

High Sucrose, Multipurpose and High Fiber Sugarcane

Most commercial sugarcane varieties have been developed to produce sugar and ethanol. Therefore they have high sucrose content and relatively low fiber content. There is an inverse correlation between juice content and fiber content of sugarcane [3].

Starting from Mauritius successful experience on electricity cogeneration the increase of sugarcane's fiber content becomes a new milestone of genetic research. Recently several multipurpose varieties and high fiber varieties have been genetically engineered. The differences between these varieties of sugarcane (high sucrose, multipurpose and high fiber) are shown in Table 4.

SCAR Morphology

The SCAR is composed of sugarcane leaves (green and dry) and cane tops (Fig. 1).The SCAR parts have different moisture content. The reported top's and green leaves moisture content is about 60–70%. The dry leaves average moisture content is 10–15% (Table 5). Contrary to the bagasse which has as a rule 50% of moisture content, the SCAR moisture content fluctuates depending on the climate and time left before their use. Generally it is recommended SCAR to rest 3 days before their use as boiler feedstock. During this time the SCAR moisture content can decrease down to 25–30% and therefore improve its combustion efficiency.

Concerning SCAR particle size, the sugarcane tops are 100–300 mm long (Fig. 9) these particle sizes are

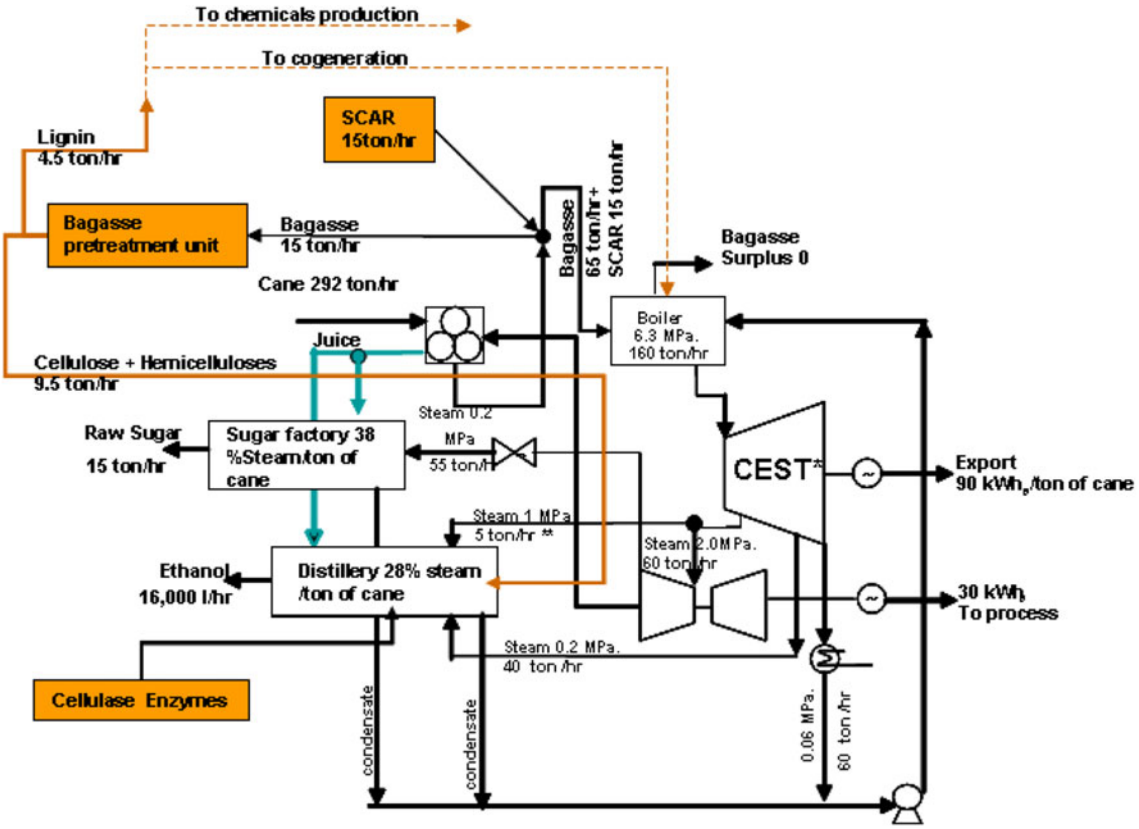

Fig. 7 Sugar mill cogeneration scheme (7,000 ton of cane/day); CEST with SCAR use and simultaneous sugar-bioethanol production (2nd generation bioethanol)

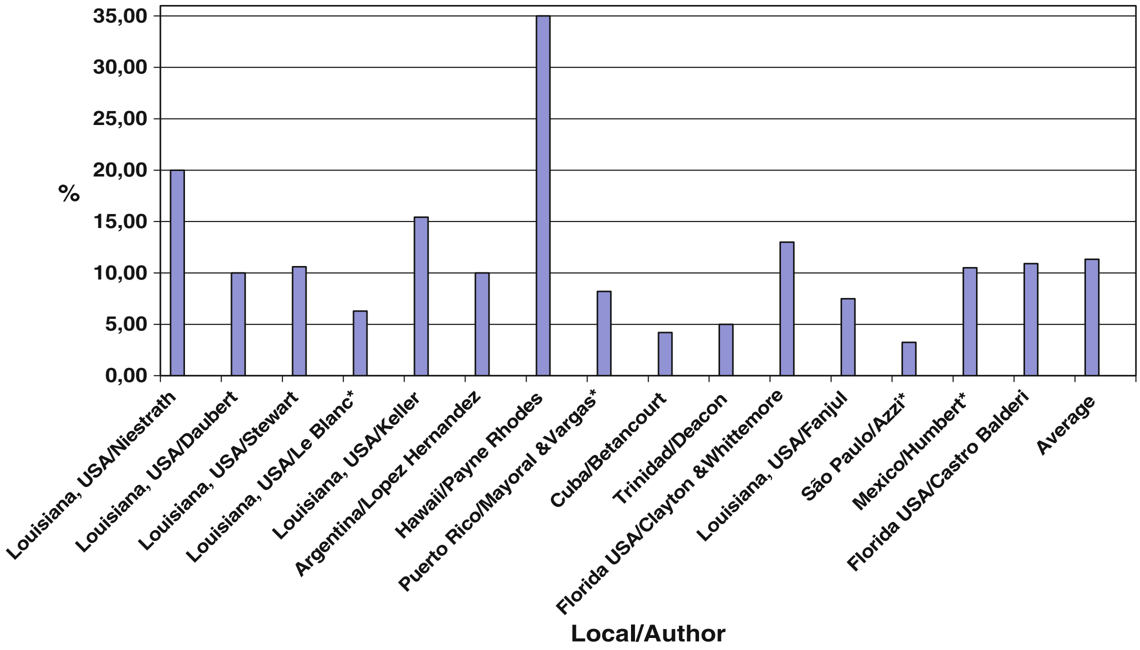

Fig. 8 Comparison of different W_{SCAR}/W_{STAK} ratio results obtained around the world [%]. * Average value. *Source* [33]

Table 4 Characteristic of high sucrose, multipurpose and high fiber sugarcane varieties

Characteristic	High sucrose	Multipurpose	High fiber
Juice Brix[a] %	20–25	18	<12
Sugarcane Brix%	16–22	14	<10
Sugarcane Pol %	12–18	<10	–
Purity %	85–92	≤65	–
Sugarcane fiber %	13–15	25–30	>30
Ratoon	3–4	6	7
Biomass ton/hectare	31	125	160

[a] Brix is a special unit used to measure the weight of solid (sugar) in 100 g of sucrose breakup

Source [46]

Table 5 SCAR parts. Their HHV and H, C content

	Mass/ton of cane [kg]	HHV[a] (MJ/kg) (db)	Hydrogen and Carbon		
			Moisture content (%)	H	C
SCAR	280	–	30–50		
Tops	86	16.4	76.8	6.3	42.1
Green leaves	110	17.4	66.2	6.4	43.4
Dry leaves	84	17.4	8.3	6.3	41.8

Source [47][a], [44]

Table 6 Bagasse and SCAR particle size comparison

SCAR particle size [mm]	Before mechanized harvesting [%]	After mechanized harvesting [%]	SCAR milled (Hammer mill 70 kg/cm^2)
≤50	7.58	10.75	65
50–100	9.87	11.50	20
100–200	29.77	53	15
>200	52.75	24.75	0
Total	100	100	100
Bagasse[a] particle size (mm)	≤50		

Bagasse as received. SCAR regarding harvesting and a complementary milling pre-treatment

Source [47], [14][a]

unsuitable for SCAR use as fuel in the boilers. The sugarcane leaves are, as a rule, 1 or 2 m long. The sugarcane is chopped by harvesting machine. The sugarcane mechanized harvesting gets hardly 10% of SCAR with a particle size like the bagasse (Table 6). After an additional milling 65% of SCAR has a particle size like bagasse and is ready to use (Table 6). In order to use of 100% of SCAR it would be necessary successive milling operations, but this procedure is very expensive and unpractical.

Environmental Aspects

Most of the recent SCAR energy studies published does not approach the environment in a systemic, detailed and comprehensive way. The environmental impacts associated with Brazilian sugarcane agro-industry have been studied by the EMBRAPA [35]. The Brazilian sugarcane agro-industry was divided in three sub-systems: agriculture, industrial and transport. The transport sub-system was

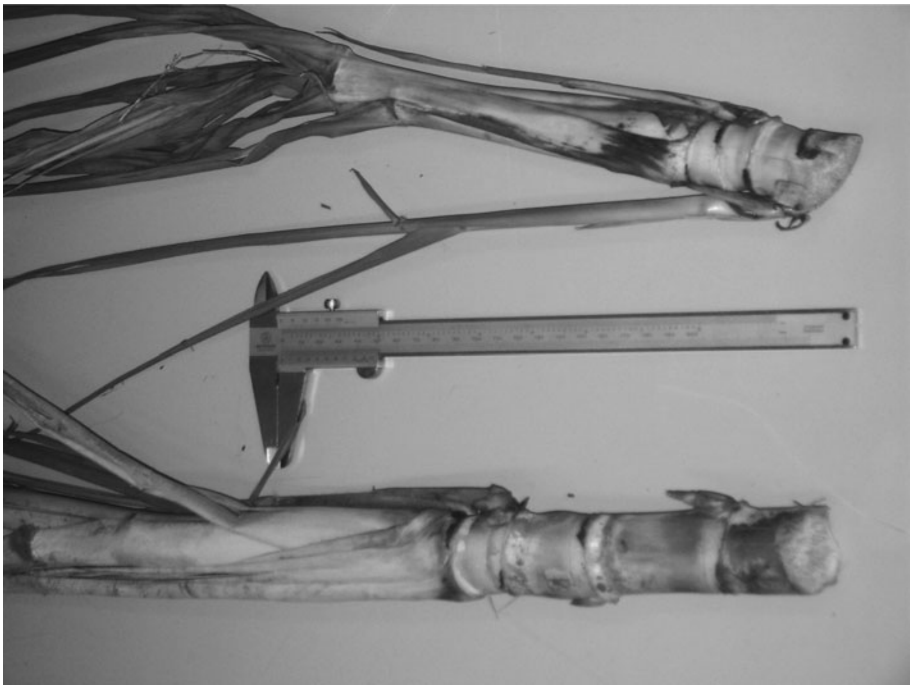

Fig. 9 Sugarcane tops compared with 250 mm caliper rule

created using bioethanol as light car fuel. The EMBRAPA has an ongoing study on sugarcane environmental impact and there is not conclusive assessment yet.

In the present work the results obtained by EMBRAPA during the study of agriculture subsystem have been partially used for the elaboration of following topics.

Avoiding GHG Emission Resulting from Burned Sugarcane Harvesting

The CO_2 emissions deserve especial mention among GHG emissions because the huge amount in which is expelled yearly as consequence of human activities. During the sugarcane growing cycle 1–1.5 years the plant captures carbon which is transformed into vegetal biomass. According to Table 1 approximately 33% of carbon captured by sugarcane is transformed into SCAR. So, the practice of burn the sugarcane before its manual harvesting releases 1/3 of all carbon content in the sugarcane.

Even the CO_2 emissions from SCAR combustion are noticeable; they result innocuous compared to fossil fuel combustion. Therefore the change in cane harvesting method from manual harvesting of burned sugarcane to mechanical harvesting of unburned sugarcane (green cane) represent an important step toward environmentally-safe SCAR energy use.

The mass of cane processed during 2007–2008 milling season in the world was $1{,}743 \times 10^6$ tons/year (Fig. 2). This sugarcane amount represent 575×10^6 tons of SCAR. Assuming a conservative average SCAR LHV Figure 15 MJ/kg, using the IPCC guidelines calculation methodology [36] and supposing that the total sugarcane processed in 2007–2008 was harvested unburned, the potential emission amount that could have been avoided would be 733×10^6 tons of CO_2.

On the other hand, if the above mentioned amount of SCAR is efficiently used for electricity cogeneration in sugar factories the electricity surplus figure could reach 4,888 GW h. Assuming that energy efficiency of a conventional thermoelectric power plant running on oil derivates is 34%, the relevant amount of fossil fuel substituted by the SCAR would be 9.27×10^6 ton of oil equivalent (toe) which also means 29.33×10^6 tons of CO_2 emissions avoided. The potential cut in CO_2 emissions resulting from harvesting a ton of unburned sugarcane (under 2007/2008 milling season conditions) could be 1.32 ton of CO_2/ton of SCAR used.

Estimating the Environmental Impacts Derived from SCAR Energy Use. Air Pollution

The change in sugarcane harvesting method from burned sugarcane manual harvesting to mechanical harvesting of green cane contribute also to diminish air pollution. The sugarcane plantation surface of a typical Brazilian sugar factory (2×10^6 ton of sugarcane/year) considering an average yield of 83 ton of sugarcane/hectare year is 346.386 km^2. A huge amount of ash (39,600–46,200 tons) is expelled as result of sugarcane burning before manual harvesting in this area. Because of milling season takes place during dry period of year the particles suspended in the air, in regions near to sugarcane plantations, frequently exceeds many times the recommended annual average for particle size 2.5 and 10 micron, respectively ($P_{M2.5}$—10 μg/m^3; P_{M10}—20 μg/m^3) [37]. The airborne particulate matter concentration beyond recommended values is directly associated with respiratory disorders of workers at sugarcane factory but also of residents in the nearest regions. The monthly airborne particulate matter concentration in the Central Region of SP state is shown in the Fig. 10. It is easy to notice that during milling season, from April to November the particulate matter concentration remains above recommended values. A maximum concentration takes place between June and October when

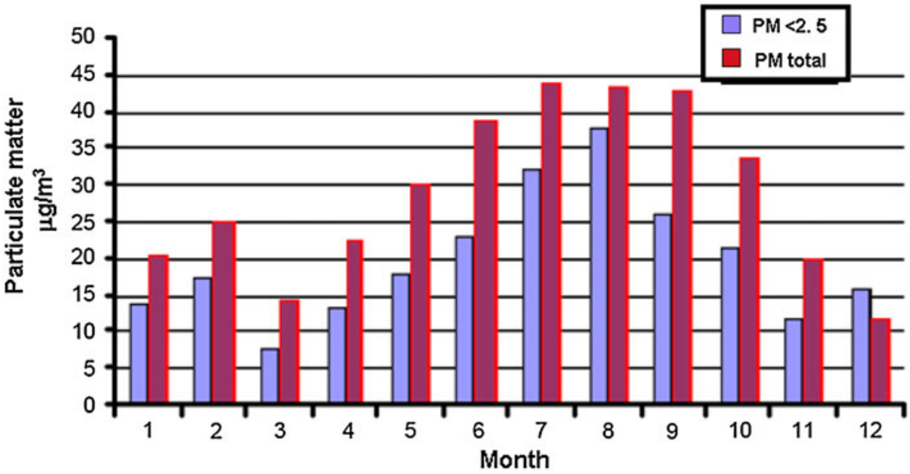

Fig. 10 Monthly distribution of particulate matter in the atmosphere. SP state central Region. *Source* [52]

$P_{M2.5}$ and P_{M10} are four and two times higher than WHO recommended values, respectively.

The phase out of sugarcane burn will undoubtedly bring a positive impact on air quality. There are not foreseen additional negatives impact derived from green sugarcane harvesting.

Water Consumption and Residues Disposal

In order to guarantee a high sugarcane yield the annual average rainfall required is 1,500–2,500 mm/year. The evapo-transpiration of sugarcane is estimated to be 8.0–12 mm/tone of cane [38]. The regions with an annual average rainfall lower than mentioned figure need additional irrigations.

The water consumption rate during sugar/ethanol production is 130 m^3 of water/ton of raw sugar or 150 $m^3$of water/850 l of bioethanol, respectively [6]. The maximal water consumption during sugar and ethanol production, in the sugar factories, occurs during sugarcane's washing (5.3 m^3 of water/ton of cane). This amount represents about 20% of all water consumed. This situation is changing with the introduction of green sugarcane harvesting, which do not need be washed.

The most important residue from bioethanol production at sugar factory is the vinasse.[4] The vinasse has a production rate of 10–13 l of vinasse/l of ethanol. In Brazil the vinasse has been successfully used for sugarcane fertilization because of its high mineral content. In order to introduce the vinasse for fertilization it is necessary preliminary studies on geology because underground water reserves could end contaminated.

There are not foreseen additional negative impacts on water consumption and residues disposal derived from the SCAR energy use introduction in the sugarcane agro-industry.

Soil Conditions. CO_2 Emissions Associated to Sugarcane Plantation Maintenance

Fertilizer, herbicide and insecticide applications should be use to obtain high yield sugarcane plantation. The annual recommended for sugarcane figures of N, P and K fertilizer are 275, 146 and 408 kg/hectare year, respectively [25]. The production of N, P and K fertilizers have CO_2 emission coefficients of 3.97, 1.30 and 0.71 ton of CO_2/ton of product, respectively [39]. The total annual CO_2 emission figure derived from fertilizer application, in the sugar plantation, is 1.572 ton of CO_2/hectare. Being that 69.4% of this value corresponds to N fertilizer.

Studies carried out in Australia on SCAR decomposition and their consequences to the soil C and N content have shown that SCAR remaining in the soil could increase by 8–15% organic C. After 3–6 years of green sugarcane harvesting practice the total soil N could increase by 9–24% and inorganic soil N could increase by 37 kg/hectare year [40]. Other results obtained, in Brazil, pointed out a bulk emission diminution of 5 ton of CO_2/hectare year [41] as result of mechanized harvesting of green cane.

The potential reduction of N fertilizer application by 9–24% and the reduction of CO_2 emitted are significant environmental advantages derived from the SCAR remaining in the field. These advantages indirectly reduce also the necessity of field equipment operations. The annual fossil fuel consumption to guarantee sugarcane plantation maintenance is 109.23 l of diesel/hectare year. This diesel represents an amount of 91.16 kg of CO_2/hectare year [36].

The change from burned sugarcane manual harvesting to mechanical green sugarcane harvesting bring clear environmental benefits associate with: soil runoff and erosion reduction; decrease of fertilizer needed [42]. Also the bacterias, fungus and microbial organisms are less affected.

SCAR Weed Control Properties

The Purple nutsedge (*Cyperus rotundus L.*) is one of most crop-damaging weeds infesting wide areas mainly in tropical and subtropical regions, causing significant sugarcane yield losses.

The herbicides and insecticide CO_2 emission factor are 25 and 29 ton of CO_2/ton of product, respectively. Considering that herbicide and insecticide annual application is 1 l/hectare year, both products, and an average density of 0.870 kg/m^3. The amount of expelled CO_2 is 0.05 kg of CO_2/hectare year.

The weed control of SCAR on Purple nutsedge was studied in Brazil. It has been verified that exists a inverse correlation between the mass of SCAR left in the field and the above ground part of purple nutsedge and also with the number of emerged sprouts.

The above ground part of purple nutsedge shown a strong negative correlation after 28–56 days associated to increment of SCAR mass. After 56 days when the SCAR layer left was 8.6 ton/hectare it was verified a reduction of above ground part of purple nutsedge [43].

On the other hand, after 28–56 days it was verified that a linear reduction of emerged sprouts with the increasing SCAR mass took place. After 84 days the number of emerged sprouts experimented a diminution when SCAR mass was 12.1 ton/hectare. The minimum figure was observed with a mass of SCAR 5.3 ton/hectare after

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[4] Vinasse- Also known as stillage, mosto, must or rum slop. Residuals from alcohol production.

84 days [43]. It was also verified that SCAR weed control properties depends on the weed contamination level and also from tubers size before harvesting. The SCAR weed control was better when tubers were small (0.2–0.3 g) than when they were large (1.0–1.1 g) [5042].

Although several studies are being carried out in order to determine the influence of SCAR use on soil compactation until today have not been quantified significant changes.

These results show that green sugarcane harvesting is far better than traditional harvesting method of burned sugarcane from soil's conditions standpoint.

Conclusions

Even though, the 2nd generation biofuels based in lignocellulosic materials, means an important event from the technological viewpoint, the introduction of SCAR energy use, in large scale, is the most significant advance from sugarcane energy efficient use. The SCAR energy use in large scale has broader and deeper impact on sugarcane business than lignocellulosic ethanol. It not only influences the industrial equipment but also sugarcane harvesting methods. Currently it is widely accepted that harvesting of burned sugarcane is a prejudicial practice. The emergence of 2nd generation biofuels, in general, and the possibility of bagasse use as lignocellulosic bioethanol feedstock, in particular, has raised an increasing interest on SCAR energy use. Since, the SCAR represents 1/3 of all sugarcane energy content, the SCAR energy use seems to be a ***sine qua non*** condition to further sugarcane agro-industry development.

The main difficulty for SCAR energy large scale use is the lack of infrastructure in the sugarcane agro- industry. Current generation of sugarcane harvesting machines was developed for SCAR disposal and not for its energy use. Most promising pathway for the 2nd generation bioethanol production is the bio-enzymatic pathway. The common sugar mill size of most factories under operation, in Brazil, is too small for BTL implementation. The SCAR use as boiler feedstock seems to be the most probable option in short and mid term.

The analysis of key environmental aspects related to SCAR energy use shows no additional threats. Actually, the SCAR energy use represents an important direct reduction of CO_2 emissions.

Although it has been demonstrated that SCAR energy use does not introduce any environmental impact, its use is insignificant. It seems to be the main reason that explain the negligible SCAR use have an socio-economic or techno-economic character. May also be a combination of both.

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